

MHD Space Sailing

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The rocket technology dates back as far as medieval China. Used initially for entertainment and religious practices over time rockets evolved into weapons and finally into means of transportation.

Today, we are nearing the top of the rockets' capabilities. Although, for now they are the only way for us to send anything into space we are becoming more and more aware of the limitations of this technology. It is essential that we invent other means of propelling probes and other interplanetary vehicles through space.

The authors had performed a series of magnetohydrodynamic simulations using the University of Chicago's Flash package to find out whether the interactions between the Solar Wind and the conducting ring with the electric current would occur. The MHD simulations gave the results similar to the monte-carlo calculations performed by dr Charles Danforth [1] from the University of Colorado. It is the authors' conclusion that the promising results should encourage further study of the phenomenon and the possibility of using it in practice.

Introduction

Rockets were known already in Medieval China. They were initially used during the religious rituals. Later they became primitive weapons. Since that time we developed technologies which allowed us to turn rockets into the only mean of sending manmade objects such as probes into far reaches of the Solar System.

The principle is simple - gain enough momentum in the first few minutes to break free from the Earth's gravity and inertially reach the desired target. The process requires lots of energy and consumes great amounts of fuel. Two limitations become apparent. Firstly, we are limited by the mass of the object we want to send. The heavier it is, the more fuel we need; the more fuel we have, the heavier the rocket and the more fuel it needs to lift itself. It seems that we reached mass limits in the 1960's and 70's when the biggest rockets such as the Saturn V were built. Secondly, once we start our journey, there's no turning back.

It is necessary, then, to find alternatives to rockets. Once we move outside the Earth's magnetosphere we could, for example, use the Solar Wind for propulsion.

In this paper we are presenting initial results of the MHD simulations performed in the Astronomical Observatory in Kraków, testing the interactions of the uniform flow of the plasma stream (representing the Solar Wind) and the magnetic field produced by a conductive ring with the electric current flowing through it. The simulations were made with the use of the FLASH 2.3 package written at the University of Chicago. The results are very interesting and hopefully will lead to further studies of the phenomenon.

The model

In this paper we're using the simplest dipole magnetic field produced by a single loop of the conductive material.

The analytical methods can describe the electromagnetic potential A around the loop with the following equation [2]:

$$A_\phi(r, \theta) = \frac{4Ia}{c\sqrt{a^2 + r^2 + 2ar \sin \theta}} \left[\frac{(2 - k^2)K(k) - 2E(k)}{k^2} \right], \quad (1)$$

with E and K being the elliptical integrals of k :

$$k^2 = \frac{4ar \sin \theta}{a^2 + r^2 + 2ar \sin \theta}. \quad (2)$$

One can only solve those analytically for small k^2 which is only valid when $a \gg r$, $a \ll r$ or $\theta \ll 1$. In these simulations we need a solution which would be valid for the whole area. We decided to use an approximated electromagnetic potential which properties would be similar to the numerical solution but which would be described with a single equation.

After some research we decided to use the following equation which we found to be a good estimate of the numerical solutions of the potential above:

$$A_\phi(\rho, z, \phi) = C \frac{R\rho}{20R^2 + z^2} \exp \left(1 - \frac{2z^2}{R^2} - \frac{20R\rho}{20R^2 + z^2} \right), \quad (3)$$

where R is the loop's radius and C is a constant containing all the physical constants. To simplify the equation the formula was chosen in the cylindrical coordinates. This form of the electromagnetic potential works best for our simulations.

FLASH

The FLASH is a simulation package created by the University of Chicago. It is written mainly in Fortran 90 and the structure allows for easy modifications of the code to suit the needs of the user. It can be used for a wide range of numerical simulations although its main function is to simulate hydrodynamical and magnetohydrodynamical problems [3].

As the initial conditions we used the magnetic field equations derived directly from the above potential equation. The initial simulations resulted in the magnetic field being carried away by the plasma outside of the simulated area. We then modified the code to freeze the evolution of the magnetic field. Unfortunately, by doing it this way we lost information about the energy required to maintain the magnetic field but our goal was only to simulate forces experienced by the loop resulting from the pressure and density changes of the plasma stream leaving the energy considerations for future research.

Results

We transformed the initial results to correspond to the following parameter values:

- the electric current $I = 1kA$
- the radius of the loop $R = 2m$
- the length of the simulation are cube $l = 120m$
- the plasma stream velocity $v = 400km/s$ [4]
- the plasma stream density $\rho = 10particles/cm^3$ [4]

We made the simulations for a series of pitch angles. Of course, in space we can only change the position of the loop but it was much easier to change the direction of the stream in the code. In each of the simulated cubes the loop was in the XY plane while the stream was coming at the angle to the XY plane.

The first and obvious result is that there is an interaction between the plasma stream and the magnetic field. That was to be expected. We then tried to calculate the overall momentum change of the stream which would tell us if we can expect any 'thrust' from the loop or not. We calculated the resultant momentum vector in the IDL package. Table 1 shows the value and direction of the resulting force.

The interesting result is that there is a non-parallel force component. At first it may seem to be a violation of a momentum conservation principle but it isn't. It is a result of an asymmetry of the magnetic field when the stream flows with pitch angles different than 0 or 90 degrees. The asymmetry makes different parts of the stream to have different lengths of their trajectories around the loop. This is very similar to the lift force resulting from the air flowing around a wing of a plane.

Table 1: The components of the force vector per volume unit in $10^{-3}N/m^3$.

angle	F_x/V	F_y/V	F_z/V	$ F /V$
0	-3.24	$-8.562 \cdot 10^{-6}$	$1.141 \cdot 10^{-6}$	3.24
30	-10.83	$4.866 \cdot 10^{-6}$	-2.24	11.06
60	19.28	$1.226 \cdot 10^{-4}$	-31.51	36.94
90	0.212	$-1.678 \cdot 10^{-5}$	-50.69	50.69

Conclusions

The first conclusion is that there is indeed a force which could be used to move objects through space. Although, the force is very small (to compare, a single engine of a Boeing 737 jet plane gives as much as about 100 kN of thrust) we studied the simplest configuration of magnetic field and its source. With stronger fields and larger areas it would cover the force may increase dramatically.

Moreover, we completely neglected the reconnection of the magnetic field. It is known that the magnetic field is carried by the Solar Wind. The pressure of the magnetic field itself may be significant but that requires more studies.

The main conclusion here should be that the entire phenomenon relatively unresearched. The initial results of the few teams which has studied it are promising. They should encourage other researchers to study the problem in much more details than presented here. It also promises that the phenomenon could be used successfully in practice.

Acknowledgements

We would like to thank dr Bogdan Wszolek for making it possible to present this paper on the YSC conference in Kiev. Also, we would like to thank everyone who shared their thoughts and ideas which were invaluable during the initial stages of the simulations.

References

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Figure 1. A simple loop of a radius a with the electric current I flowing through it.

Figure 2. Vectors of magnetic field \vec{B} in the XZ plane.

Figure 3. Density of the plasma stream with the relative pitch angle between the stream and the loop of 0, 30, 60 and 90 degrees.

Figures are available on YSC home page (http://ysc.kiev.ua/abs/proc14_9.pdf).